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Effect of Particle Sources on the Structure of the H–mode Pedestal

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ABSTRACT. Techniques of dimensional analysis have been applied to deuterium and hydrogen plasmas in DIII–D to test the postulate that the edge particle source plays a role in forming the edge H–mode density profile. These experiments show that the pedestal density scale length is typically a factor of two to three larger in hydrogen plasmas than in deuterium plasmas with dimensionally similar ion parameters. These results are in agreement with the postulate [1,2] that the density scale length is primarily determined by the local particle source, rather than by the shape of a hypothetical particle transport barrier. The electron temperature scale length displays a similar trend, albeit with a weaker density dependence. Thus the pedestal pressure gradient scale length is larger in hydrogen. It is also observed that the frequency of a coherent mode, localized within the pedestal, increases with the local density (ie inversely with the local density scale length) irrespective of the working gas species. This frequency is a factor of two lower in a hydrogen discharge than in a dimensionally similar deuterium plasma, a result which cannot be explained solely in terms of plasma physics variables.

INTRODUCTION. Understanding the physics of the H–mode pedestal is of great importance to achievement of an economic fusion power reactor. Pedestal conditions greatly influence confinement and through ELMs the life expectancy of the divertor components. One of the key issues is what physics determines the structure of the density profile in the vicinity of the pressure pedestal. It has been proposed [1] that the H–mode pedestal density scale length is primarily determined by the particle source profile, which is expected to have a characteristic width of the neutral mean-free-path, rather than by the structure of a hypothetical particle transport barrier. In other words, the particle source profile is narrower than the width a particle transport barrier. Recent experiments on DIII–D [2] showed that the shape of the density profile is qualitatively and semi quantitatively consistent with predictions of neutral mean-free-path model of the density profile described in Ref. [1]. In contrast, plasma similarity experiments between DIII–D and C-MOD, which ignored particle sources and atomic physics [3], appeared to show that the width of the density profile is proportional to the device size. This result is not necessarily in conflict with the particle source model of the pedestal density profile if the poloidal distribution of the particle source in C-Mod was more uniform than in DIII–D.

One possible way to study these issues would be to make direct measurements of the neutral source in an H-mode plasma. However, due to strong toroidal and poloidal variations in the recycling source, a sufficiently accurate measurement of the ionization source profile is not practical in DIII–D at this time. An alternative approach to resolve this issue is to compare pedestal profiles of plasmas with different ion masses but with the same dimensionless plasma ion parameters in the same device, assuming that ion physics determines heat and particle transport. Since the neutral mean-free-paths would not necessarily be matched in such an experiment, particle source effects might be isolated from the plasma physics effects. This experiment has been done in DIII–D, as reported below, and indeed it is found that the width of the density barrier does not scale with the dimensionless plasma variables but does scale as expected with the neutral mean free path.

THE EXPERIMENTS. Our goal was to compare the pedestal profiles of dimensionally similar deuterium and hydrogen plasmas of identical geometry and matched dimensionless parameters: $\nu_I^* \propto qn_I / T_I^2$, $\rho_I^* \propto (T_I\, m_I)^{1/2}/B_T$, $\beta_I \propto n_I T_I / B_T^2$ and q at the top of the pedestal in the DIII–D device. Because of the close coupling of T_I and T_e, ν_e^* and β_e were also expected to be reasonably matched. However, ρ_e^* can not simultaneously be matched. Matching of these parameters required T_I (D) = 1.41 × T_I (H), n_I (D) = 2 × n_I (H), and B_T(D) = 1.68 × B_T (H). Since, for a fixed poloidal distribution of the recycling neutrals, the width of the particle source profile λ_s scales approximately as $1/\left(m_I^{0.5} n_I\right)$ [1], λ_s in hydrogen is expected to be a factor of 3 larger than in similar deuterium plasmas. If the particle source profile is not important within a hypothetical particle transport barrier, the width of the density profile is expected to be nearly identical in the two plasmas. On the other hand, if the boundary plasma density profile is determined by the local particle source, the density scale length should be much larger in hydrogen than in deuterium.

In the actual experiment, we were unable to increase the pedestal value of the ion temperature in the deuterium plasma to match that of the reference hydrogen plasma by increasing the auxiliary heating power, although the volume average beta in deuterium surpassed that of the hydrogen plasma. As a result, only ρ_I^* was reasonably matched in a pair of discharges.

Since the DIII–D graphite walls are loaded with copious amounts of deuterium, several discharges with simultaneous hydrogen gas puff and divertor cryopumping were required to achieve a desired ~80% isotopic purity. Concentrations of the two isotopes were measured by two independent techniques of emission spectroscopy and by neutron flux due to D-D fusion reactions involving 80 kV ions, deposited by short neutral beam blips [5], and the background plasma ions. Boundary plasma electron density and temperature profiles were measured by Thomson scattering (TS). The density profiles were also measured by microwave reflectometry. Ion temperature profiles were obtained by charge exchange recombination (CER) spectroscopy. In order to obtain good statistics, TS data between ELMs were averaged over periods of several hundred milliseconds. The edge electron density profiles were then fitted to a function of the form $a + b\mathrm{Tanh}\{(x-c)/d\}$ [4], where x is the distance from the separatrix and a, b, c and d are fit constants. The density pedestal width is defined as $\lambda_n = d\text{-}c$, which is representative of the density gradient scale length within the separatrix. The location of the separatrix was determined by the EFIT MHD code [6].

Pedestal parameters of deuterium and hydrogen plasmas are compared in Table 1. Discharges 110194 and 111296 have the closest match of the dimensionless parameter $\rho_I^* \propto$

Shot #	gas	n_e PED	T_e PED SEP	T_I PED SEP	B_T	q_{95}	$n_e T_I/B^2 \propto \beta_I$	$qn_e/T^2 \propto \nu_I^*$	$(T_I M)^{0.5}/B \propto \rho_I^*$	$(T_e m)^{0.5}/B \propto \rho_e^*$	λ_T	λ_n	ln Model
110166	D	0.37	800 51	1200 710*	2.0	3.3	110	8.3 E-7	25	14	1.5	1.26	1.3
110169	D	0.38	740 130	750 435*	2.0	3.3	71	2.2 E-6	19	14	0.95	0.78	1.2
110192	H	0.43	320 39	330 225	1.2	3.1	99	1.2 E-5	15	15	1.29	1.11	0.9
110194	H	0.3	377 38	340 200	1.2	3.1	76	8.5 E-6	15	15	0.91	0.91	0.96
111296	D	0.6	420 130	350 220– 321	2.0	3.5	57	1.9 E-5	13	10	0.82- 0.90	0.30- 0.59	0.52- 0.6

Units: T(eV), n(E20 m–3), B_t(T), γ(cm), *Estimate

$(T_I\ m_I)^{1/2}/B_T$. Temperature and density profiles from this pair of discharges is shown in Fig. 1. We observe that λ_n in hydrogen is a factor of 2-3 larger than in deuterium. In contrast, the pair of discharges 110192 and 110166, with similar pedestal densities but large differences in ν_I^* and ρ_I^*, display similar λ_n values. These results indicate that ν_I^* and ρ_I^* have little effect on the pedestal density. The β values could not be matched to better than 30%. Experimentally, it was difficult to increase the pedestal β in the deuterium plasma 111296 to the level of the hydrogen discharges by increasing the heating power, even when the average β of the entire plasma surpassed that of the hydrogen plasma. It can not be ruled out that the factor 2–3 difference in λ_n in the matched pair of discharges is due to the mismatch in β values. However, the fact that pedestal β saturated in the deuterium suggests that other processes other than pure plasma physics might be involved.

It is possible that the mismatch in ρ_e^* is responsible for the variations in λ_n. This possibility can not be excluded by comparing the data of Table 1 since λ_n is correlated with ρ_e^*. This correlation is expected since the pedestal T_e varies as $1/n_e$, therefore at constant toroidal field $\lambda_n \propto 1/n_e \propto \rho_e^{*2}$. We expect to address this issue in a future experiment.

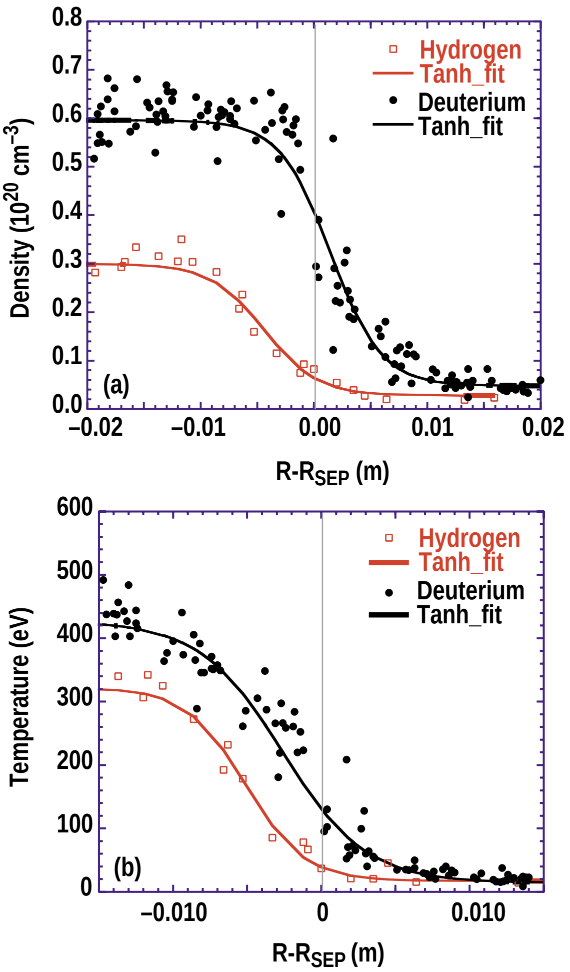

Fig. 1. (a) In dimensionally similar D and H plasmas density width is larger in lower density H plasma, (b) in dimensionally similar D and H plasmas temperature width are nearly equal.

The last two columns in the table compare the experimental values of λ_n with predictions of a modified version of the analytical model of Ref. [1]. The new version includes the contribution of Frank-Condon neutrals to the particle source inside the separatrix. A free parameter in the model is the quantity $f(\theta_0)$ defined as the ratio of $d\psi/dr$ at the location of recycling source relative to $d\psi/dr$ at the location where the density profile is measured or mapped (normally the outer midplane), where ψ is the poloidal flux. When the neutral source is concentrated in a region of large flux expansion (i.e. small $d\psi/dr$), flux surface averaged neutral penetration is reduced, which results in a steeper density profile. In the model, the density scale length inside the separatrix is directly proportional $f(\theta_0)$. The last two columns in Table 1 compare the experimental density scale length with the predictions of the analytic model. Here $f(\theta_0)$ is determined by fitting the model results to the density profiles of the two hydrogen discharges. Then it is seen that the model predicts the scale length for the remaining discharges fairly accurately.

At all densities in both deuterium and hydrogen plasmas, Beam Emission Spectroscopy (BES) detected a pronounced coherent mode of a frequency of a few tens of kHz. For the deuterium discharges the frequency of the mode increased roughly linearly with the pedestal density. For the pair of matched discharges, the laboratory frequency of the mode was a factor of two lower in hydrogen, presumably due to the lower density of the hydrogen plasma. This density dependence of the frequency of the mode could also be a manifestation of the steepening of the edge pressure gradient.

CONCLUSIONS AND DISCUSSION. For hydrogen and deuterium discharges in which the dimensionless parameter ρ_I^* was matched on the pedestal, the density pedestal width did not remain constant, but decreased with increasing density, as expected from the neutral mean free path. The density width differs by about a factor of two-three for matched discharges. This observation is in agreement with the postulate that the width of the density pedestal is approximately the same as the width of the ionization source profile.

Although λ_n shows a stronger dependence on density than does the scale length for the electron pressure λ_p, λ_n is always within a factor of two of λ_p. A possible explanation for this result is that the width of the transport barrier is indeed determined by the density profile, as proposed by Hinton [7]. Hinton gives the following expression for the flow shear at the plasma boundary, assuming that the bulk poloidal and toroidal flow contributions to the flow shear are negligible: $du_{ExB}/dr \approx (c/eB)\ dn_I/dr\ dp_I/dr$. This expression shows that the component of the flow shear, due to dp_I/dr is significant only within the density pedestal. Thus it is plausible to expect the edge transport barrier to be approximately as wide as the density pedestal width, which in gas fueled discharges is equal to the neutral mean free path. If this picture is correct, then it is expected that the transport barrier would become wider with a deeper fueling source, such as a stream of shallowly deposited pellets.

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